Effective Lagrangians and Physics Beyond the Standard Model

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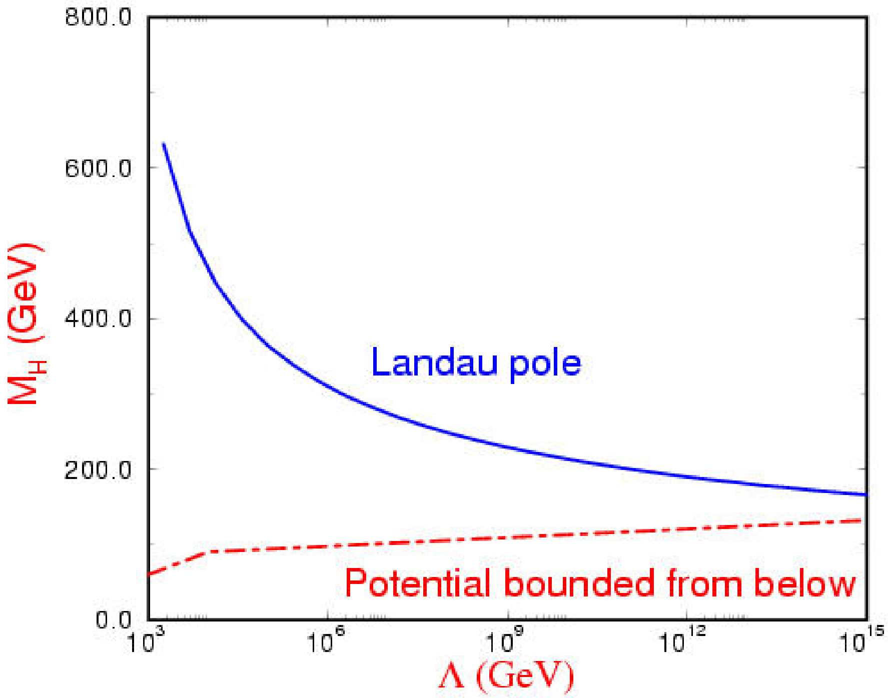
TASI06

Lecture 5

SM Higgs Boson

- Theory is perturbatively consistent only within chimney



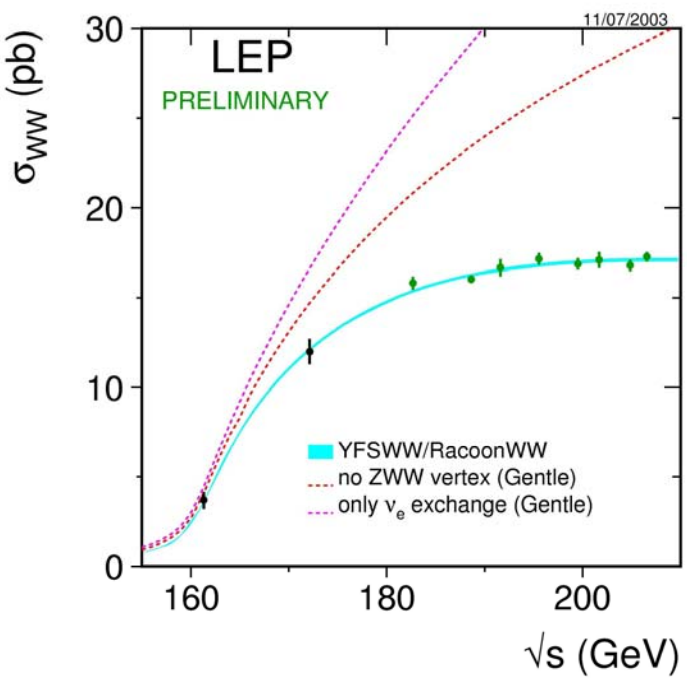
Theory is perturbatively unitary

- At all energies if: $\boxed{M_h < 800 \text{ GeV}}$

- For infinitely massive (or no) Higgs at energies less than:

$$\boxed{E_c \sim 1.7 \text{ TeV}}$$

The theory works



Effective Field Theory

$$L = L_{SM} + \sum \frac{c_i}{\Lambda^2} O_i^{\,6} + \ldots..$$

- Effective Lagrangian
- O_i contain light fields
- All information about heavy degrees of freedom in c_i
- Categorize operators by their dimensions, d_i
- Operators with $d_i > 4$ suppressed by powers of E/Λ

Operating assumption is that $\Lambda \gg M_Z$

Counting Dimensions

- Fermions: dim=3/2
- Gauge bosons/scalars: dim=1
- ∂: dim=1
- SM Lagrangian is dimension 4
- Only 1 SU(2) x U(1) invariant dimension 5 operator:
  - $L_5=(L\Phi)(L\ \Phi)/\Lambda \rightarrow (Lv)(Lv)/\Lambda \rightarrow m_\nu \nu\nu$
  - $\Lambda \sim 10^{15}$ GeV

Many Possible Dimension-6 Operators

$$\mathcal{L}_6 = QQQL, L\sigma^{\mu\nu}W_{\mu\nu}He, \\ W^{\mu}_{\nu}W^{\nu}_{\lambda}B^{\lambda}_{\mu}, (H^{\dagger}D_{\mu}H)(H^{\dagger}D^{\mu}H), \cdots$$

Philosophy: We don't know what the physics at high energy scales is

We assume it respects the SU(2) x U(1) symmetry

Little Hierarchy Problem

- Much possible new physics is excluded at the TeV scale
  - Look at possible dimension 6 operators
    - Many more operators than shown here
  - Limits depend on what symmetry is violated

New operators	Experimental limits
$\frac{(\bar{d}s)(\bar{d}s)}{\Lambda^2}$	$\Lambda > 1000\ TeV$
$\frac{m_b(\bar{s}\sigma_{\mu\nu}F^{\mu\nu}b)}{\Lambda^2}$	$\Lambda > 50\ TeV$
$\frac{(h^+D_\mu h)^2}{\Lambda^2}$	$\Lambda > 5\ TeV$
$\frac{(D^2h^+D^2h}{\Lambda^2}$	$\Lambda > 5\ TeV$

New Physics typically must be at scale $\Lambda > 5$ TeV

Schmaltz, hep-ph/0502182

No Higgs?

- Remember, Higgs is used to unitarize the SM
- Unitarity violated at 1.7 TeV without a Higgs
- This sets the scale for something new
- Construct the Standard Model without a Higgs
  - Higgs is only piece we haven’t seen experimentally

Standard Model Revisited

- Scalar sector described by SU(2) doublet

$$\Phi = \frac{(v+h)}{\sqrt{2}} e^{i w^a \sigma^a / v} \qquad V = \frac{\lambda}{4}\left[Tr\left(\Phi^+ \Phi\right) - \frac{v^2}{2} \right]^2$$

- Scalar potential invariant under global $SU(2)_L$ x $SU(2)_R$ symmetry:

$$\Phi \to L \Phi R^+$$

- Global symmetry broken by

$$< \Phi > = \frac{v}{\sqrt{2}}$$

Higgsless Standard Model

- Construct most general effective Lagrangian with 2 derivatives describing Goldstone bosons with global $SU(2)_L$ x $SU(2)_R$ symmetry

- This construction is expansion in powers of E^2/Λ^2

$$L = \frac{v^2}{4} Tr\left[\partial_\mu \Sigma \partial^\mu \Sigma^+\right] \qquad \Sigma = e^{i w^a \sigma^a / v}$$

Assume $\delta\rho = 0$

Higgsless Standard Model, #2

Gauge theory: $$L = \frac{v^2}{4} Tr\left[D_\mu \Sigma D^\mu \Sigma^+\right] + (kinetic)$$

$D_\mu\Sigma = \partial_\mu\Sigma - igW_\mu\sigma/2\Sigma + ig' B_\mu\Sigma\sigma^3/2$

Unitary gauge is $\Sigma=1$

This is SM with massive gauge bosons

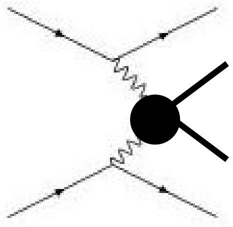
At $O(E^2/\Lambda^2)$ gauge couplings are identical to those of the SM

Higgsless Standard Model, #3

- Add $O(E^4/\Lambda^4)$ operators
  - Contributions from $O(E^2/\Lambda^2)$ operators generate infinities (SM is not renormalizable without Higgs)
  - These infinities absorbed into definitions of $O(E^4/\Lambda^4)$ operators
  - Can do this at every order in the energy expansion
- Coefficients are unknown but limited by precision measurements
  - A particular model of high scale physics will predict these coefficients
- The $O(E^4/\Lambda^4)$ terms will change 3 and 4 gauge boson interactions

WW scattering at LHC

- Four gauge boson interactions are sensitive to unitarity violating physics (Vector boson fusion)
- Look for W^+W^-, ZZ, $Z\gamma$, $W\gamma$ pair production in vector boson fusion
  - Consistent expansion in powers of E^2/Λ^2



V=W,Z,γ

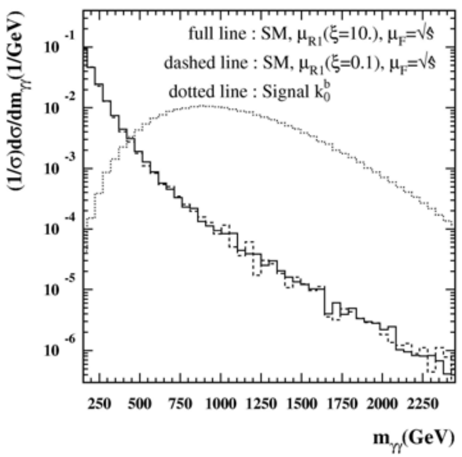
WW Scattering without a Higgs

- Add terms of $O(E^4/\Lambda^4)$ to effective L

$$L = ... + L_1 \left(Tr\left(D_\mu \Sigma D^\mu \Sigma^+\right)\right)^2 + L_2 \left(Tr\left(D_\mu \Sigma D^\nu \Sigma^+\right)\right)^2 + ...$$

LHC

  - This Lagrangian violates unitarity
  - n derivative vertex $\approx E^n/\Lambda^{n-4}$
- This is counting experiment (no resonance)
  – Example: Search for anomalous $WW\gamma\gamma$ vertex through gauge boson fusion



Normalized to show difference in shape of signal and background

Hard!

Eboli et al, hep-ph/0310141

Contruct Models without Higgs

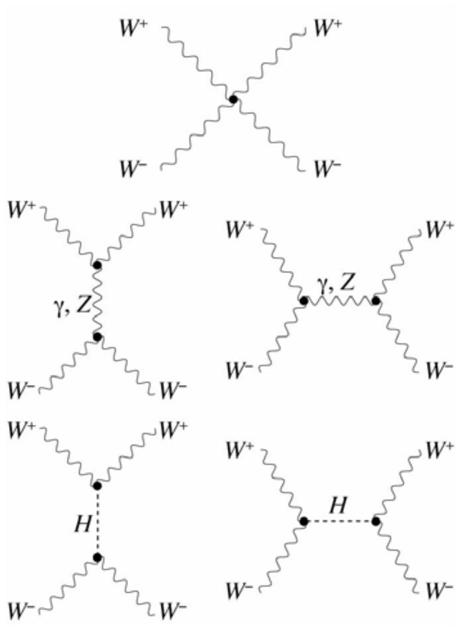
- Problems with unitarity
- Something must come in to conserve unitarity if theory is to remain perturbative
- Extra dimension “Higgsless” models have tower of Kaluza Klein particles
  - These look like heavy copies of the W, Z, and photon

Models without Higgs have difficulties with Unitarity

- Without Higgs, *W*-boson scattering grows with energy

$$A \sim G_F E^2$$

  - Violates unitarity at 1.7 TeV
- SM Higgs has just the right couplings to restore unitarity
- Extra D models have infinite tower of Kaluza-Klein states
- Need cancellations both in E^2 and E^4 contributions to amplitudes
- Arrange couplings to make this happen

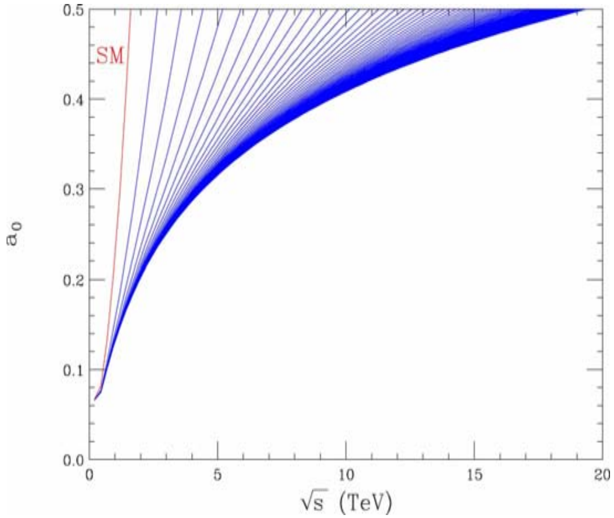


Look for heavy gauge bosons

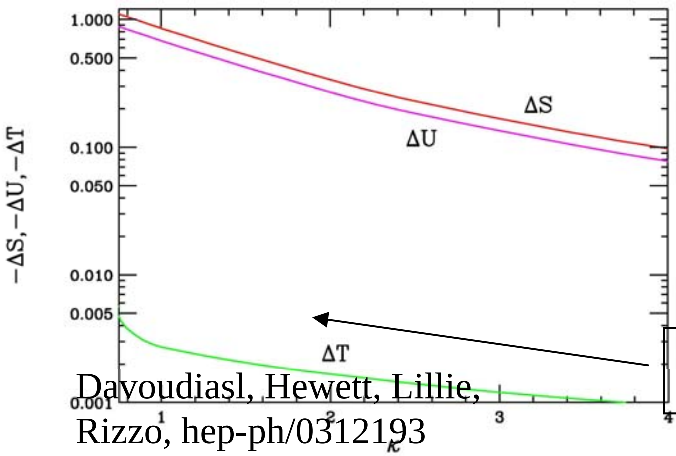
Higgsless phenomenology

- Tower of KK vector bosons
  - Can be produced at LHC, e^+e^-
- Tension between:
  - Unitarity wants light KK
  - precision EW wants heavy KK

J=0 partial wave for WW scattering



Foadi, Gopalakrishna, Schmidt, hep-ph/0312324



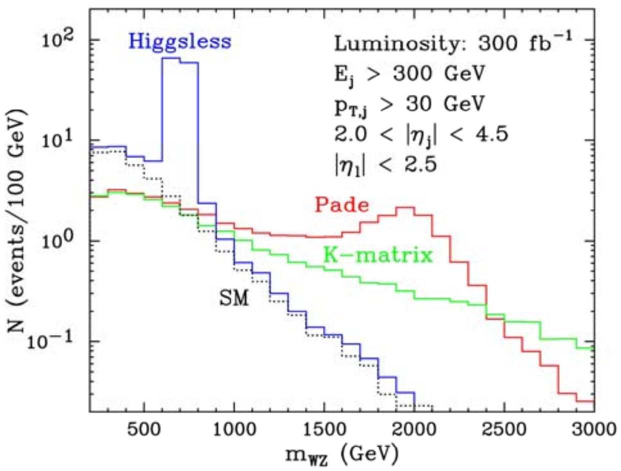
Davoudiasl, Hewett, Lillie, Rizzo, hep-ph/0312193

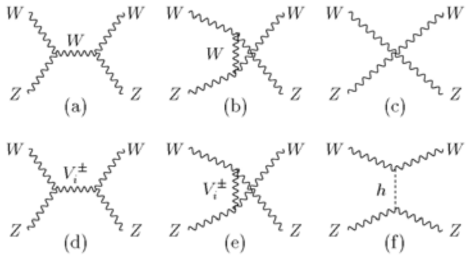
Heavier $\kappa \rightarrow$ heavier KK gauge bosons

Experimental Signatures of Higgsless Models

- Look for massive W, Z, γ like particles in vector boson fusion
  - Need small couplings to fermions to avoid precision EW constraints
  - Narrow resonances in WZ channel

LHC



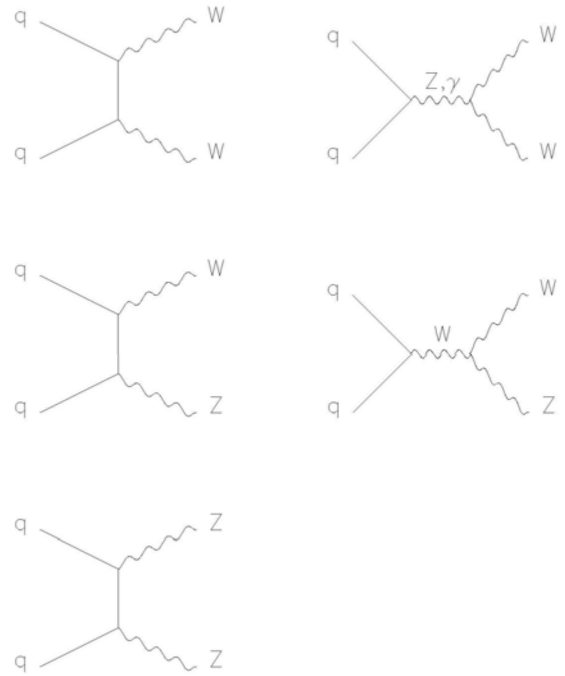


Different resonance structure from SM!

Birkedal, Matchev, Perelstein, hep-ph/0412278

Gauge Boson Pair Production

- W^+W^-, $W^\pm\gamma$, etc, production sensitive to new physics
- Expect effects which grow with energy
  - $A_t \sim (\ldots)(s/v^2)+O(1)$
  - $A_s \sim -(\ldots)(s/v^2)+O(1)$
  - $\sigma_{TOT} \sim O(1)$
- Interesting angular correlations: eg $W^\pm\gamma$, has radiation zero at LO



Remember $e^+e^- \to W^+W^-$

Non-SM 3 gauge boson couplings spoil unitarity cancellation

Consider Non-SM W^+W^-V Couplings

- Most general gauge and Lorentz invariant couplings with C and P separately conserved

$$\frac{L_{VVV}}{-ig_V} = g_1^V (W_{\mu\nu}^+ W^{-\mu} V^\nu - W_\mu^+ V_\nu W^{-\mu\nu}) + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{M_W^2}$$

- Where V=Z,γ
  - λ_V higher order in derivative expansion (often ignored)
  - SM: $\kappa_\gamma = \kappa_Z = g_1^Z = g_1^\gamma = 1$, $\lambda_V = 0$
  - EM gauge invariance requires $\Delta g_1^\gamma = 0$
- Often assume $SU(2)_c$ and neglect higher dimension operators
  - $g_1^Z = \kappa_Z + \tan^2\theta_W \Delta\kappa_\gamma$
  - $\lambda_V = \lambda_\gamma$

A model of BSM will specify these anomalous couplings

What size effects can we hope to see?

- NLO corrections to W^+W^- known
- Can hope to see small BSM effects
  - At the Tevatron: $p\overline{p} \rightarrow W^+W^- \rightarrow e^+e^- p_T^{miss}$

Theory $\rightarrow$ $\boxed{\begin{aligned}\sigma_{LO} &= 62\ fb \\ \sigma_{NLO} &= 82\ fb\end{aligned}}$

$$p_T^e > 20 GeV$$
$$|\eta_e| < 2.5, |\eta_e| < 2.5,$$
$$p_T^{miss} > 20 GeV$$
$$p_T(jet) > 20 GeV$$

- With Non-SM couplings:

$$\Delta g_1^Z = .5, \lambda_Z = \lambda_\gamma = .1, \Delta\kappa_Z = \Delta\kappa_\gamma = .3$$

$$\boxed{\begin{aligned}\sigma_{LO} &= 83\ fb \\ \sigma_{NLO} &= 107\ fb\end{aligned}}$$

But don't precision measurements require a light Higgs?

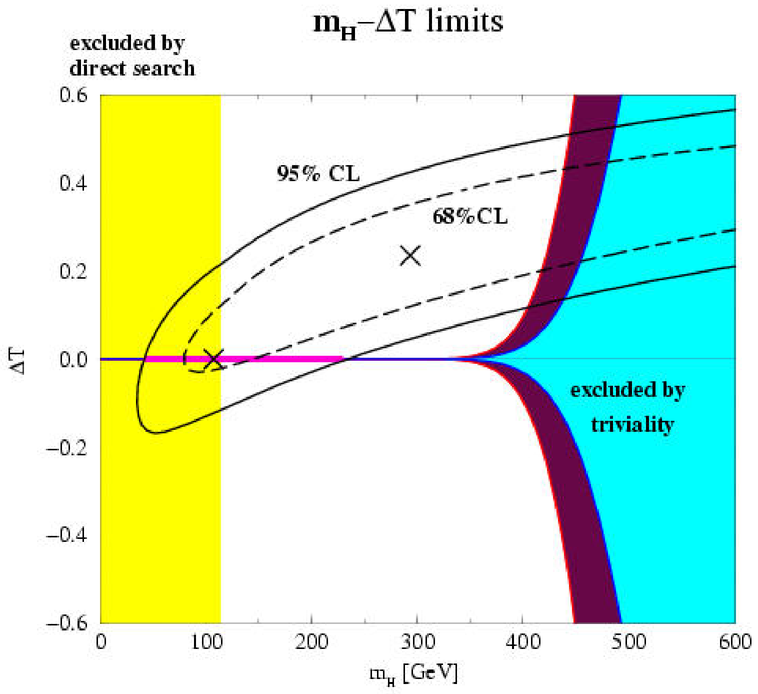
- Higgs mass limits from precision measurements assume SM
  - Suppose the SM is effective low energy theory valid to scale Λ
  - Include all operators allowed by SU(3) x SU(2) x U(1) gauge symmetry (and assume a light Higgs)
  - Include effects of new operators in fits

$$\boxed{L = L_{SM} + \sum \frac{c_i}{\Lambda^2} O_i^{\,6} + ...}$$

Higgs can be heavy with new physics

- $M_h \approx$ 450-500 GeV allowed with large isospin violation, ΔT

Constructing actual models with this feature is hard



•Chivukula, Holbling, hep-ph/0110214

Much Activity in EW Scale Model Building

- Remove Higgs completely
  - Dynamical symmetry breaking
  - Higgsless models in extra D
- Lower cut-off scale
  - Large extra dimensions
- Force cancellations of quadratic contributions to Higgs mass
  - SUSY
  - Little Higgs
  - Make Higgs component of gauge field in extra D

Much more satisying to have a model than just an effective theory!

Strong limits from precision measurements

Symmetries maintain cancellations at higher order!

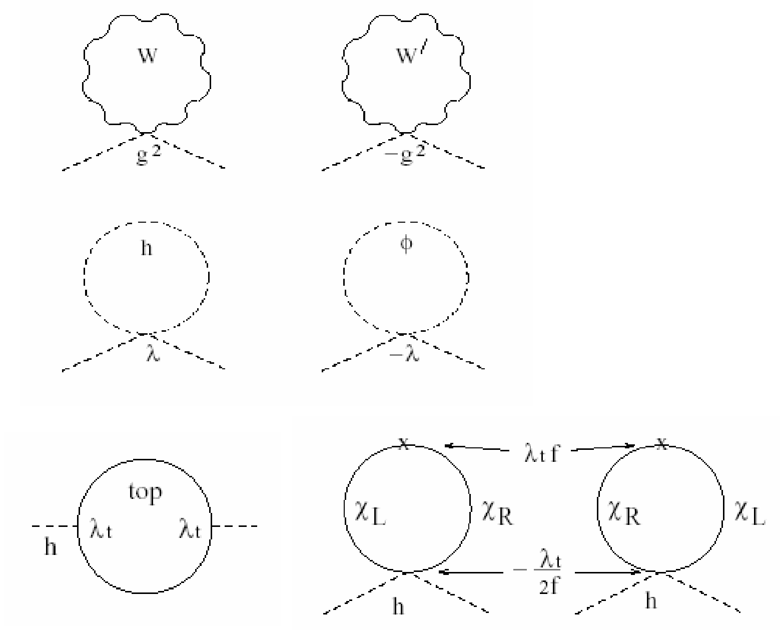
Little Higgs Models

New particles at scale $f \sim \Lambda$ cancel SM quadratic divergences

Cancellation from same spin particles

Need symmetry to enforce cancellation

- Heavy W_H, Z_H, A_H cancel gauge loops
- Scalar triplet cancels Higgs loop
- Vector-like charge 2/3 quark cancels top loop



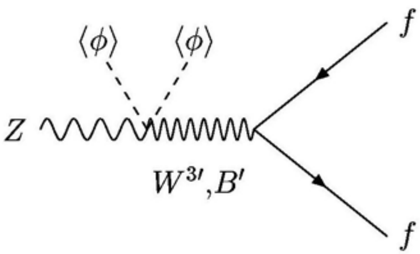
Arkani-Hamed, Cohen, Katz, Nelson, hep-ph/0206021

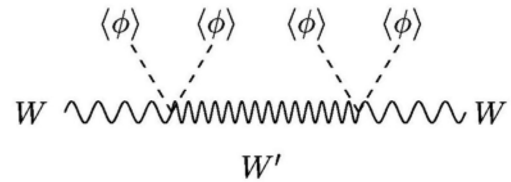
More on little Higgs

- Global Symmetry, G (SU(5))
  - Broken to subgroup H (SO(5)) at scale $4\pi f$
- Higgs is Goldstone Boson of broken symmetry
  - Effective theory below symmetry breaking scale
- Gauged subgroups of G $([SU(2)xU(1)]^2)$ contain SM
- Higgs gets mass at 2 loops (naturally light)
- Freedom to arrange couplings of 1st 2 generations of fermions (their quadratic divergences small)

- Heavy W's, Z's, γ's
- Heavy top
- Extended Higgs sector

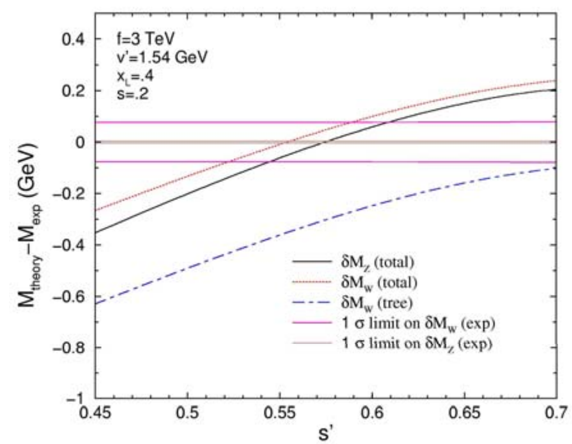
Little Higgs & Precision EW





- Mixing of heavy-light gauge bosons leads to problems with precision measurements

$$\boxed{\begin{aligned}\frac{\delta\Gamma_Z}{\Gamma_Z} &\approx 1+(\ldots)\frac{v^2}{f^2}\\ \frac{\delta M_W{}^2}{M_W{}^2} &\approx 1+(\ldots)\frac{v^2}{f^2}\end{aligned}}$$



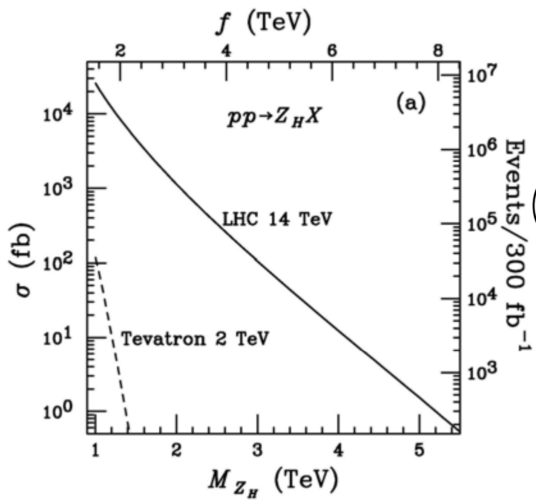
- Many models
- Triplets cause problems with ρ parameter unless VEV small
- Typically, $f \geq 3-4\,TeV$

Chen& Dawson, hep-ph/0311032

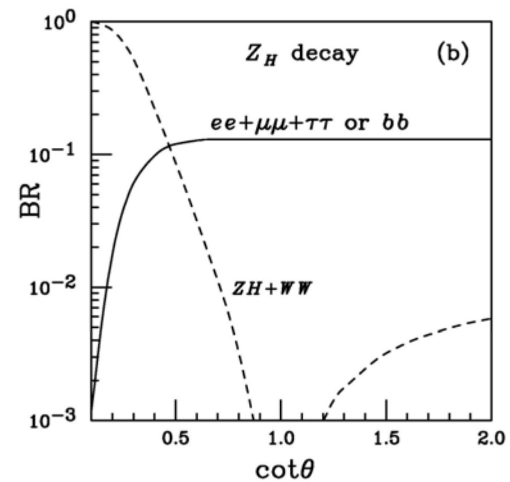
New Phenomenology in Little Higgs Models

- Drell-Yan production of Z_H
  - EW precision limits prefer cot θ≈.2 (Heavy-light gauge mixing parameter)
  - BRs very different from SM
  - $M_{Z_H}^2 \approx M_Z^2 f^2/v^2$
- Look for heavy tops
- Look for non-SM 3 gauge boson vertices

Han,Logan,McElrath, Wang, hep-ph/0301040



Scale down by $\cot^2\theta \approx .04$

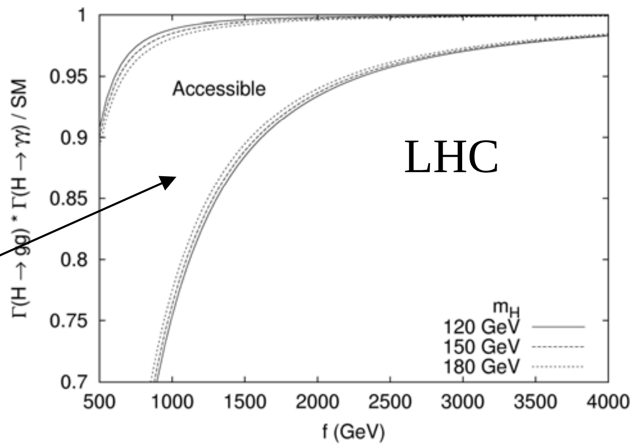


Higgs production & decay in Little Higgs Models

•Growing realization that EWSB isn't just Higgs discovery, but requires finding spectrum of new particles!

- Rate could be reduced by ≈25%
- Have to see new particles
  - Z_H, W_H, γ_H

$gg \rightarrow h \rightarrow \gamma\gamma$



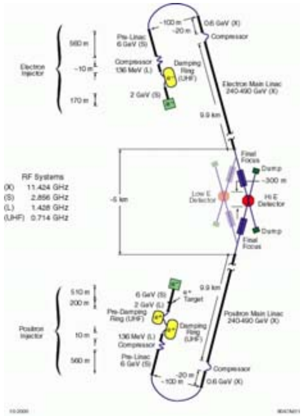
This is theoretically allowed region

Han, Logan, McElrath, Wang, hep-ph/0302188

Possibilities at the LHC

- We find a light Higgs with SM couplings and nothing else
  - How to answer our questions?
- We find a light Higgs, but it doesn't look SM like
  - Most models (SUSY, Little Higgs, etc) have other new particles
- We don't find a Higgs (or any other new particles)
  - How can we reconcile precision measurements?
  - This is the hardest case

Science Timeline



Tevatron	LHC	LHC Upgrade	LC
2004	2007	2012	2015?

This is the decade of the hadron colliders!